THE MARS ROVER MOBILITY SYSTEM

The Mars Pathfinder SOJOURNER Rover vehicle has completed its mission. It explored the vicinity of the lander, probing the Martian surface while getting pictures of the rocks and the way they are arranged. It analyzed the chemical make up of the soil and the various rocks. It dug into the surface, measuring the soil strength and the abrasive characteristics. It has done all that was expected of it and more. In accomplishing all this it has demonstrated a mobility which exceeds conventional all-terrain vehicles by a wide margin.

Several things had to be considered in the design stage of this semi autonomous vehicle which was sent a long way without the ability to be serviced. Reliability involved more than simply not breaking down. The device had to be able to negotiate the terrain without getting jammed or hung up. At the design stage this involved not only the actual make up of the planet, but also any imagined situations which might occur. Smooth glassy volcanic rock with little or no friction and talcum powder like dust at depths greater than the vehicle height are examples of things we were delighted to not find. As it turned out, there is a bit of over kill in the design.

The wheel cleats protrude 10 millimeters and dig into the sand to provide excellent tractive force. This feature complicates the autonomous navigation by changing the effective rolling radius over soft surfaces and hard surfaces. The cleats were formed from 0.127 millimeter stainless steel. This makes a rather sharp cleat which will grip on the slightest irregularity. Several pictures have been released which show how the wheels climb right up the face of a rock. The wheels are 79 millimeters wide. When they sink to their design depth for soft material they have a ground pressure of only 1.65 killopascals. The average automobile has a ground pressure of around 240 killopascals and army tanks have around 48. No condition experienced on Mars actually required this low pressure. Flotation and a good bit of the traction come from the wheels, but the ability to climb obstacles is primarily a function of the suspension system. The rover suspension system is a unique configuration which evolved over the last several years. It has been called the "Rocker-Bogie" system because the front and center wheels are joined on each side to form bogies. These bogies pivot freely at the front of rocker links. The rockers each have a rear wheel at the other end. The rockers are freely pivoted at a point near their middle. These pivots are where the body attaches. The body is controlled in the pitch direction by a set of links which form a differential, keeping the body at an average angle between the two rockers. There are no springs or intentionally elastic members in the system. When a wheel is suspended with an elastic system, the downward force increases as the wheel is raised according to the spring rate of the system. This increase in force makes it more difficult to raise at the same time it takes downward force away from the remaining wheels reducing their traction.

Studies were performed in the late 1980's by contractors to the Jet Propulsion Laboratory regarding the various types of vehicle configuration.. Many types were studied and the serious contenders were; wheels, track laying, and simple legged configurations. Simple legged vehicles are those with restricted degrees of freedom. The more complex legged designs which are intended to climb and leap like spiders and mountain goats have challenging mechanical design problems that we all wanted to work on. The control problems are overwhelming. The most complex issue is "seeing" ahead and planning foot placement. Simple legged vehicles are variations on the walkers used by the physically impaired. They place one set of feet forward while standing stably on another set. Weight is then transferred to the forward set in order to form a new stable configuration, and the process is repeated. Wheeled vehicles won on the basis of simplicity, efficiency, light weight, and ease of control. Four wheeled vehicles are the simplest, most efficient, lightest in weight, and easiest to control. They do not climb obstacles very well however. We are talking about obstacles that are larger than the diameter of the wheels. For example, take the configuration in Fig 3 which has a wheelbase equal to three and one half wheel diameters and a center of gravity midway between the wheels. If we place a vertical wall in front of both front wheels, the front will rise when the coefficient of friction is 0.778 or greater. The bottom of the rear wheel drives at ground level and the wall resists at axle height. This results in a moment which lifts the front. The friction at the front raises the vehicle with a moment arm equal to the wheelbase plus the radius of the front wheel. The center of gravity resists with a moment arm of half the wheelbase. When the wall is placed in front of the rear wheel, the coefficient of friction required becomes 1.4 or greater. The wall reacts at axle height and the front wheel pulls at ground level resulting in another moment which tends to lift the front. The friction at the rear raises the vehicle with a moment arm equal to one half of the wheelbase minus the rear wheel radius. The center of gravity resists with a moment arm in this case of one half the wheelbase minus the radius.

By increasing the complexity 50% more, six wheels can be made to climb vertical walls on both sides when the coefficient of friction is a value of 0.8 . The Sojourner rover will climb in the forward direction with coefficients of 0.5, 0.68, and 0.6 for the three wheel positions in order, and in reverse with coefficients of 0.78, 0.75, and 0.82 . Eight wheels will perform even better, but the doubling of the complexity and the problems associated with steering make it impractical. Having more wheels is better because the one or two that are climbing are pushed against the obstacle(s) by the others. This results in more climbing traction. At the same time, a lesser fraction of the weight is being lifted.

The vehicle has to be stable at all times. It has to be able to stop at any point and be able to proceed or reverse. This includes being able to stop while climbing a vertical wall. For this reason the first analyses were done toward optimization of climbing vertical bumps that are axle high and above. Bumps is a class of obstacles which fits between the wheels so that all wheels not climbing are on a single plane. Another class of obstacles is steps. Steps carry the vehicle from one level to another. Step climbing looks more spectacular to watch, but is actually easier than bump climbing. The reason is that the rear wheels are hoisted by the rest of the vehicle and the lifting force is a downward force on the wheels up on the step, increasing their traction. Bumps on the other hand, cause the forward wheels to be dragged backwards as the rear climbs. The downward force of the climbing wheel in this case tends to lift the forward wheels reducing their traction. While steps are rare on Mars, bumps are common.

The process of optimization began by solving for the coefficient of friction required to climb vertical surfaces at each of six positions (in front of and behind each pair of wheels, front center, and rear). This made it a two dimensional problem by taking both sides of the vehicle up the obstacle at once. This was an arbitrary requirement used to compare vehicle configurations. It is considerably less difficult to climb an obstacle on one side only. A seventh position was added later to analyze the four wheeled situation when the rover "pops a wheelie" raising the front wheel(s) as a result of resistance at the rear. The linkage proportions were traded in a way to minimize the limiting coefficient of friction. Later a deliberate change was made to lengthen the front of the bogie link making it easier to back out the front wheels. The resulting configuration was compared to the results of other analyses. The key other analysis solved for the steepest angle that can be climbed when the coefficients of friction are known. In this set of analyses, the coefficient of friction was different on the horizontal than on the obstacle. The most popular set was a coefficient of 0.8 on the obstacle and 0.3 on the horizontal. This is for climbing rocks in sand. All these analyses assumed unlimited torque available at every wheel. The actual flight design is capable of a tangential force on each of the wheels equal to one half the weight of the entire vehicle on earth.

Ground clearance is one of if not the most important aspect of an all terrain vehicle. The ground clearance is set at one and one half wheel diameters. The body has a belly pan designed to support the entire weight. This belly pan is considered part of the mobility system. Theoretically it is possible to balance the rover on an obstacle where it can neither go forward nor back off. This was never seen in field testing. After extensive testing in the desert and in the laboratory on earth, performing in the 3/8 gravity of Mars is a "piece of cake".

The final design steers the wheels at all four corners. Experimental models were made with all six wheels steerable. The resulting versatility was not considered worth its weight. The vehicle does perform well in a crabbing maneuver even though the center wheels aim forward. Crabbing is when the vehicle moves sideways in a crab like fashion. With all four corner wheels aimed diagonally towards one side, the center wheels scuff sideways contributing only forward thrust. As the vehicle crabs, it translates to the side without changing heading. This maneuver was successfully performed on Mars. Normal steering is of the Ackerman type where the axes of all wheels coincide at a single point. This point is the center of rotation. Because each wheel is steered independently, this center can be situated anywhere along the centerline of the middle wheels. When the wheels are turned in a crossways manner, this center of rotation can be at the center of the vehicle. This turns out to be the most popular maneuver because the navigation system gets a change in direction without a change in position. The very first turn made by the rover after it backed down the ramp was to turn around in place leaving the donut visible in pictures sent to earth. The suspension works in a turn. Picture sequences sent back and put on the webb show the vehicle turning and climbing rocks at the same time.

The rover has the ability to easily climb obstacles which are more than 30% of its length. These obstacles can be overrun both straight on and while turning at will. By comparison, the average family sedan could drive unconstrained over one and one half meter obstacles. After the configuration was decided, it became necessary to make the vehicle squat down to save space. Originally the rover was to be on the base petal of the lander and straddle some of the electronics under its body in the ground clearance space. The actual electronics are housed in the large white many-faceted thermal enclosure with thick walls. The rover had to be mounted to one of the side panels where the only thing it straddles is solar cells. Squatting down is accomplished by "breaking" the rocker links where they pivot on the body. The rover stands up by driving the rear wheels forward with the remaining wheels locked. After the rocker links are arched to their full height, a mechanism on each side snaps into place locking them into position forever. This mechanism is a coil spring tightly wound to its solid height and bent over to where the opposite ends almost touch when the rover is down. After the full height is reached, the spring snaps straight to become a ridged compression member. The differential is active in the standing up process. It keeps the body parallel to the panel as it stands. (See fig. 2) This is accomplished by joining the differential arm on the rocker to the front of the right side and to the rear of the left side. With the vehicle folded, the differential behaves as though there is a very large obstacle at the right front and another at the left rear. As the vehicle stands, both these obstacle angles decrease and the differential keeps the body parallel to the point where it locks in place. In order to pull this off, it is necessary to break the rocker links at a place where the front and the back parts rotate through the same angle. This involved putting a kink in the front half of each rocker link in order to clear the center wheel when folded. To make the suspension links strong in torsion as well as bending in all directions, they are machined each from a single piece of aluminum. There are no seams to concentrate loads or welds to weaken the metallurgy. A type of tee slot milling cutter is put through the holes and the center of the beam is cut away. The proportions of the member are varied along its length. The resulting closed section has its moments Ixx and Iyy independently variable.

To borrow a phrase which is common in today's advertising "this vehicle outperforms everything in its class". The engineering staff at JPL fantasizes over what it would be like to drive a vehicle eight times the rover's size.

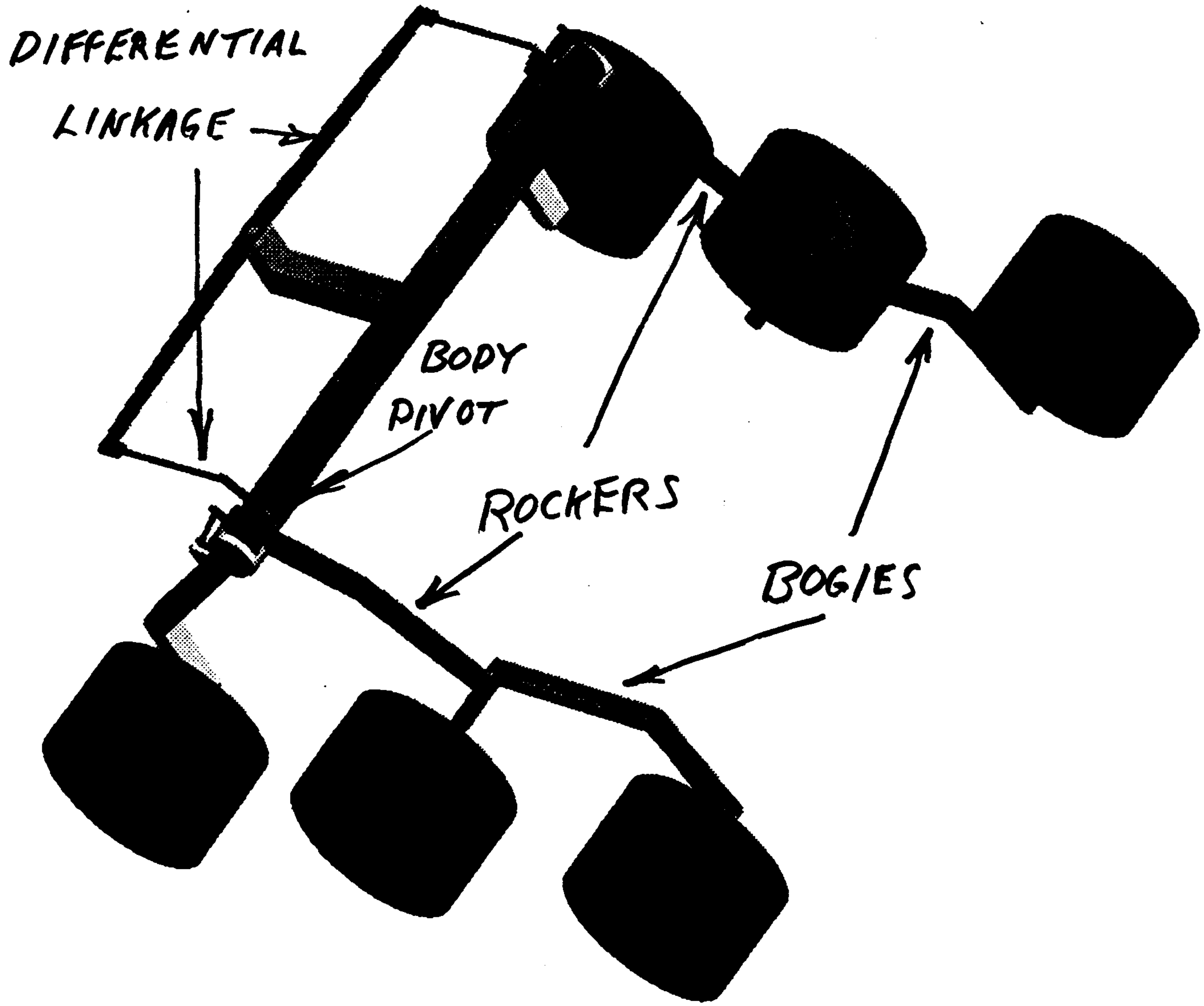


FIG 1

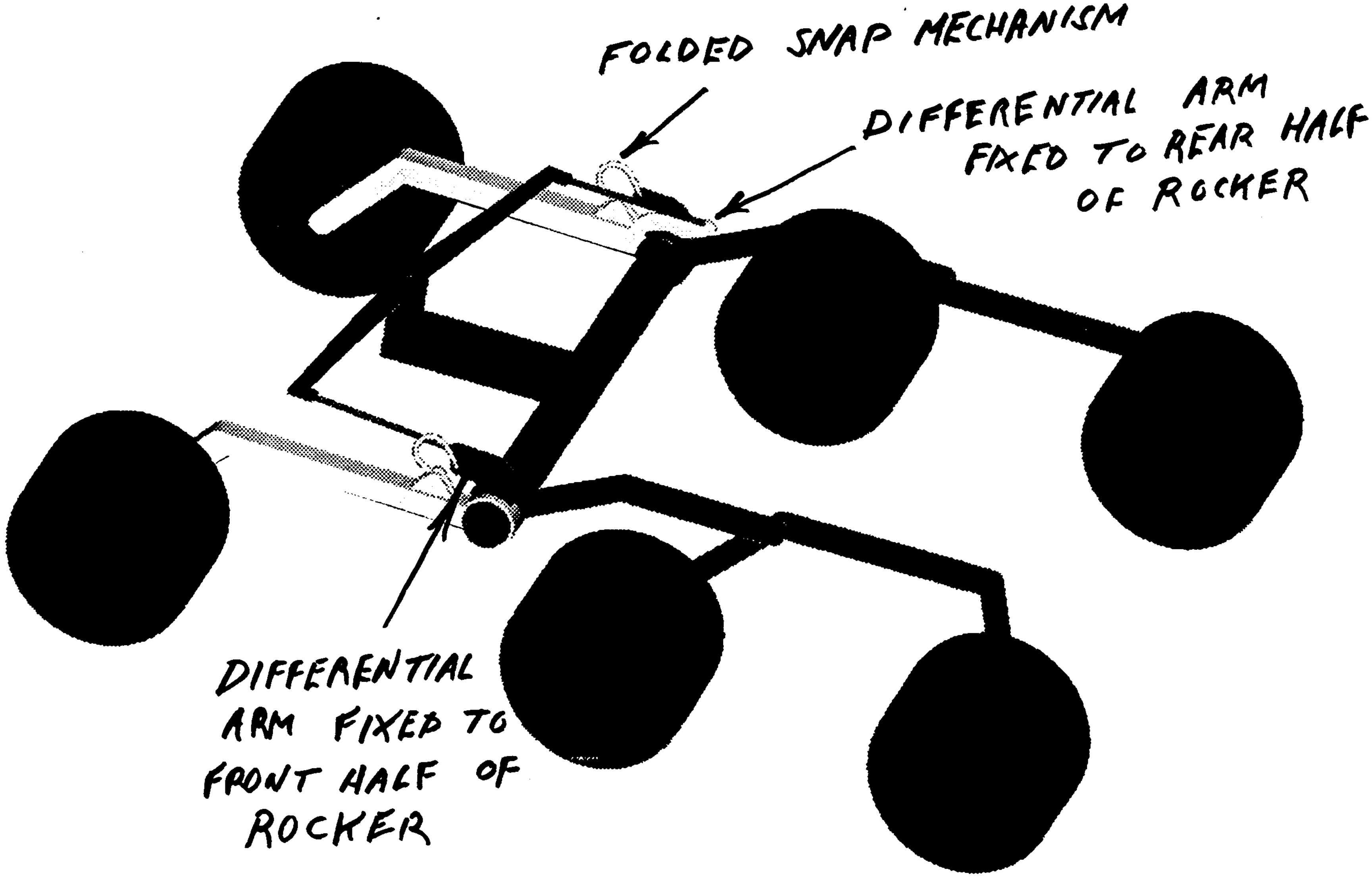

FOLDED SNAP MECHANISM
DIFFERENTIAL ARM FIXED TO REAR HALF OF ROCKER
DIFFERENTIAL ARM FIXED TO FRONT HALF OF ROCKER

FIG 2

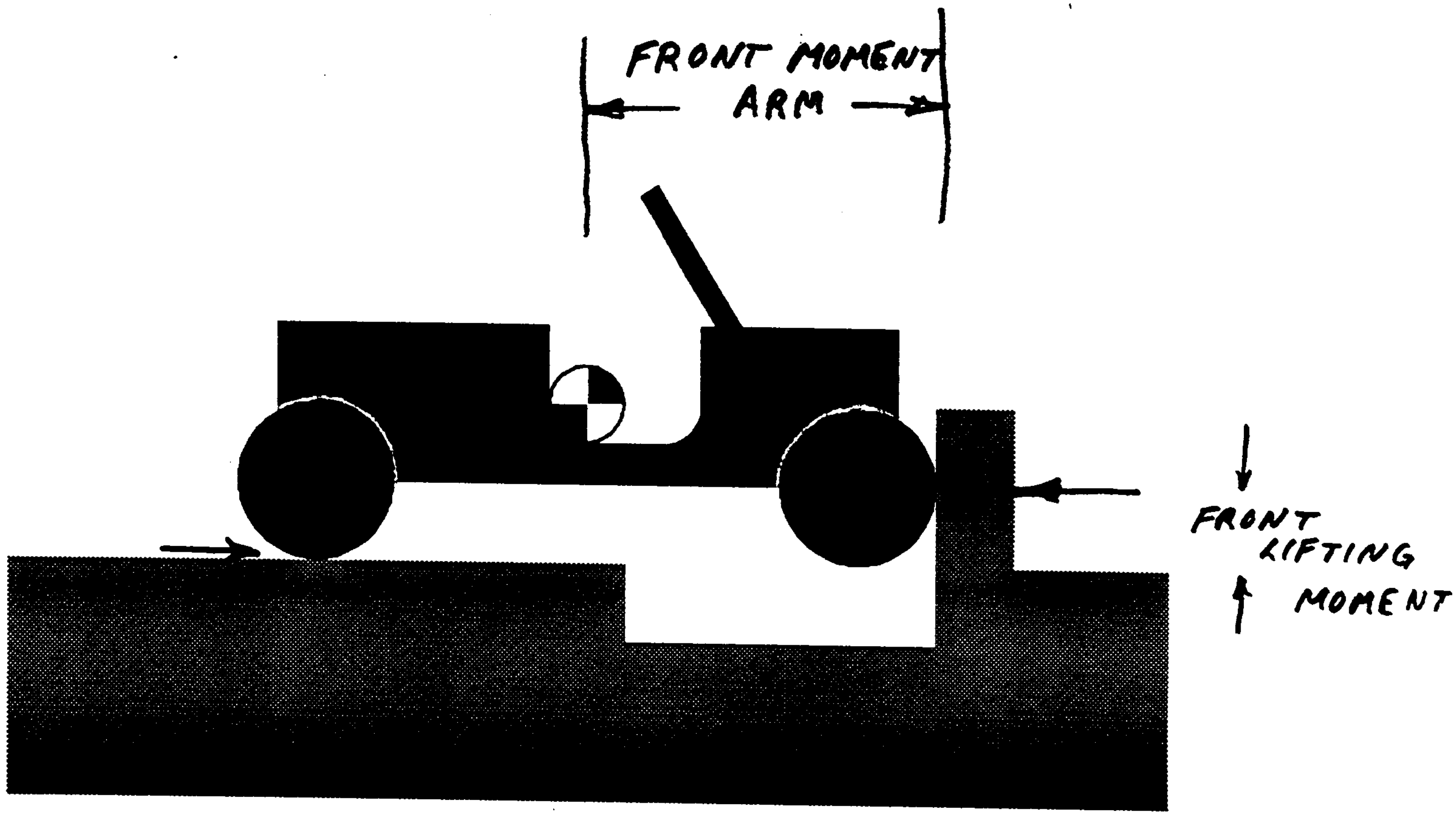


Fig 3 A

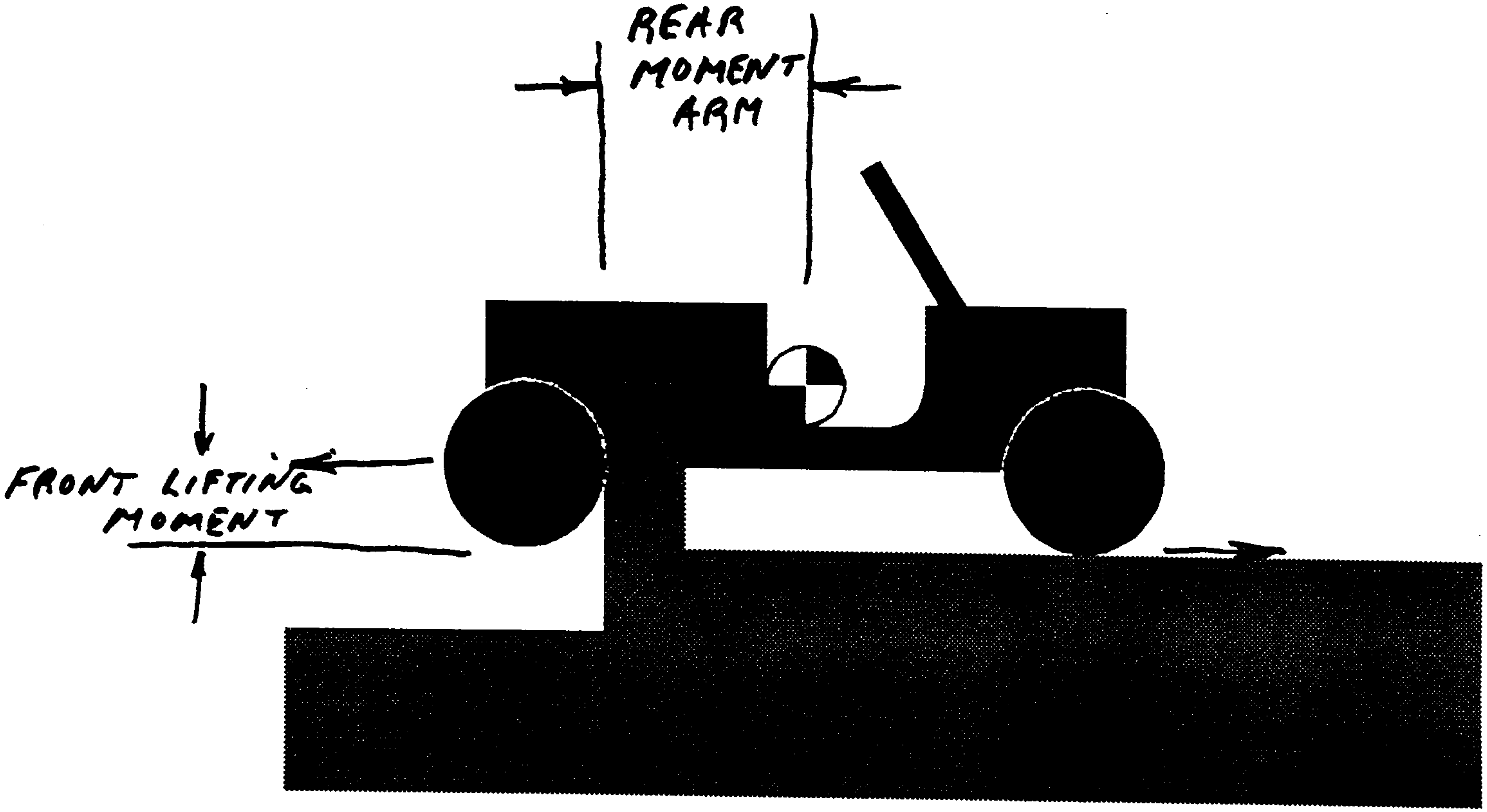
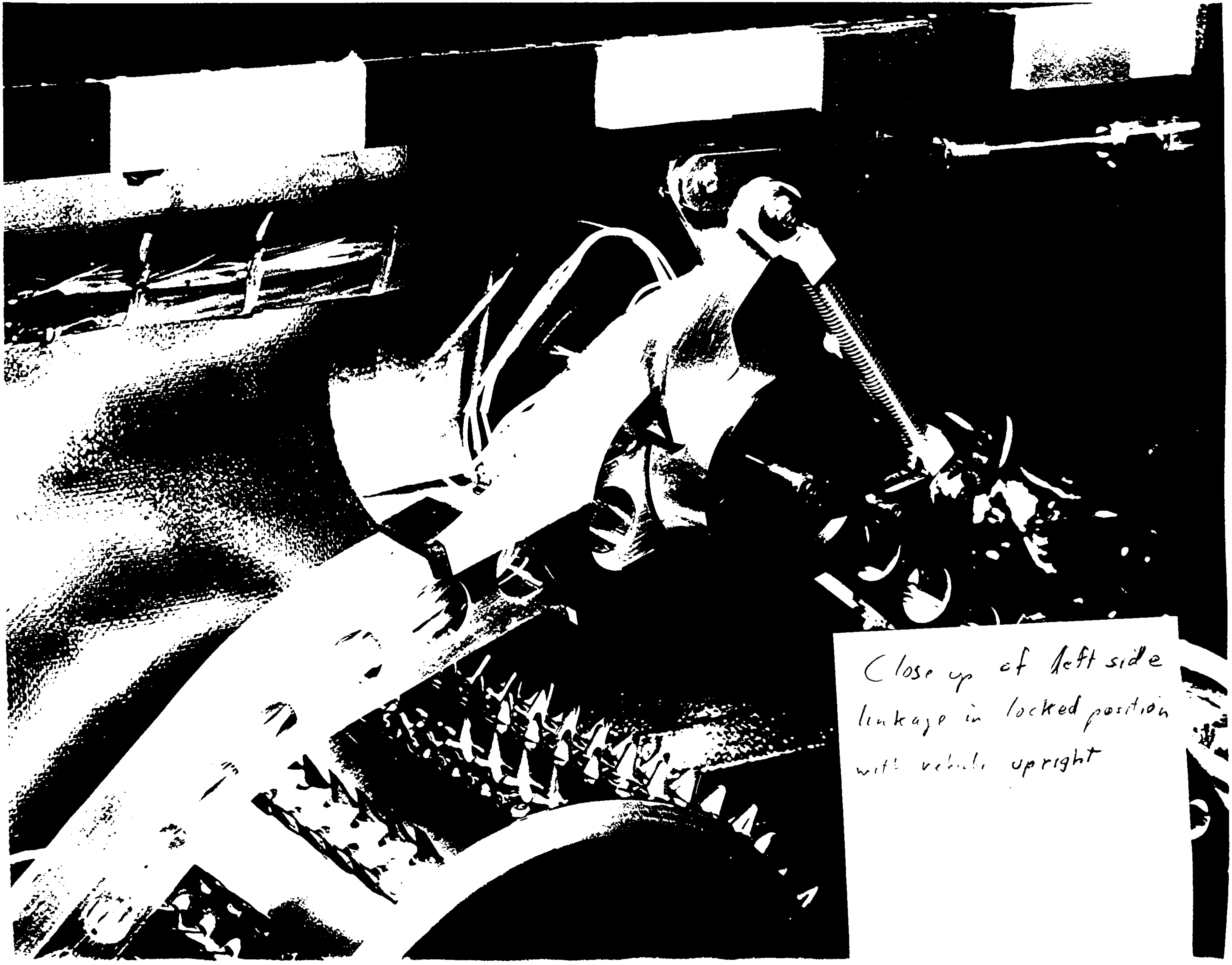
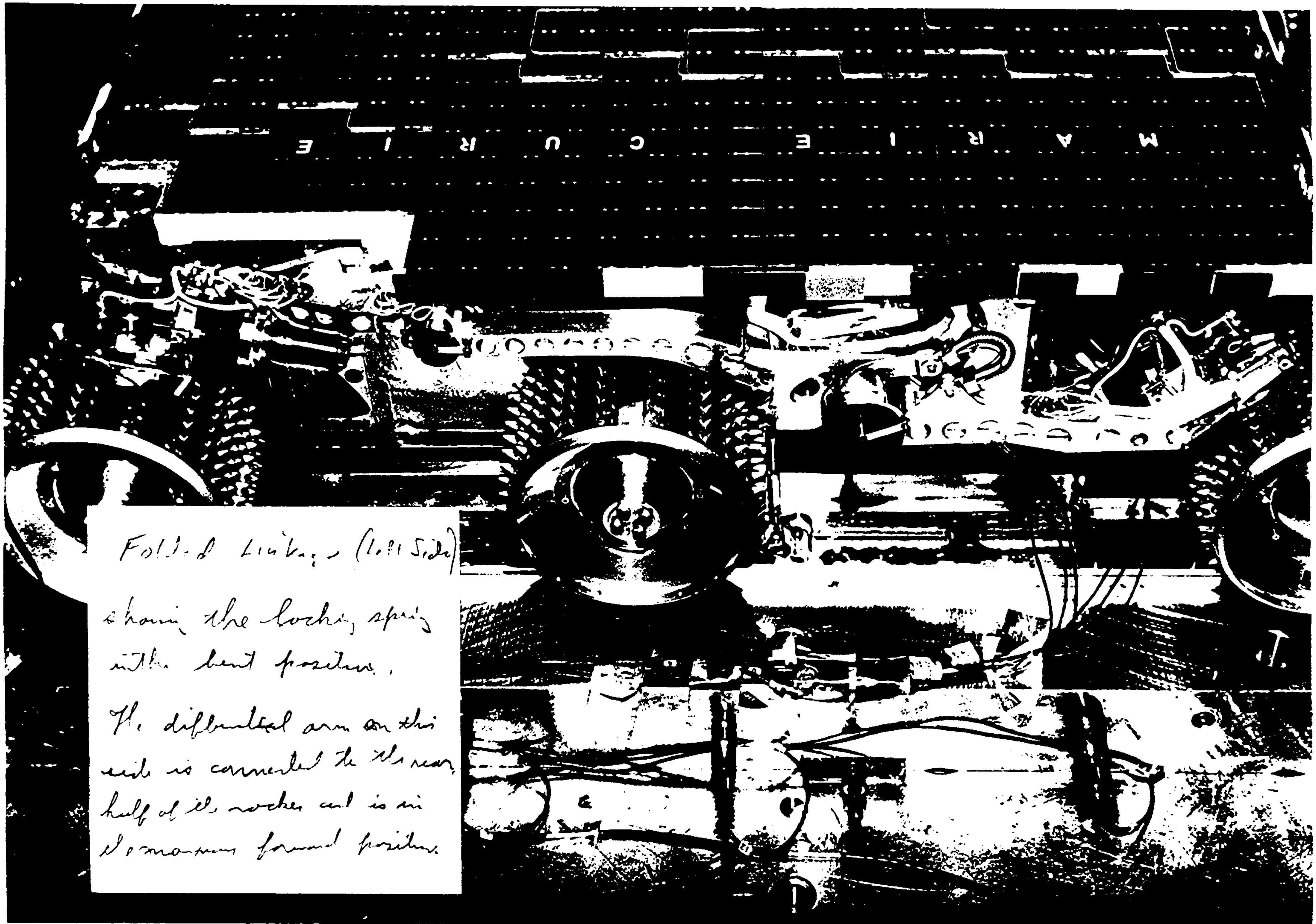


Fig 3 B



Close up of left side
linkage in locked position
with vehicle upright



Folded Linkage (Left Side)

showing the locking spring in the bent position.

The differential arm on this side is connected to the rear half of the rocker and is in the maximum forward position.

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